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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : H01J 49/00

A2

(11) International Publication Number: WO 99/35668

(43) International Publication Date: 15 July 1999 (15.07.99)

(21) International Application Number: PCT/GB99/00009

(22) International Filing Date: 12 January 1999 (12.01.99)

(30) Priority Data: 9800488.0 12 January 1998 (12.01.98) GB

(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published

Without international search report and to be republished upon receipt of that report.

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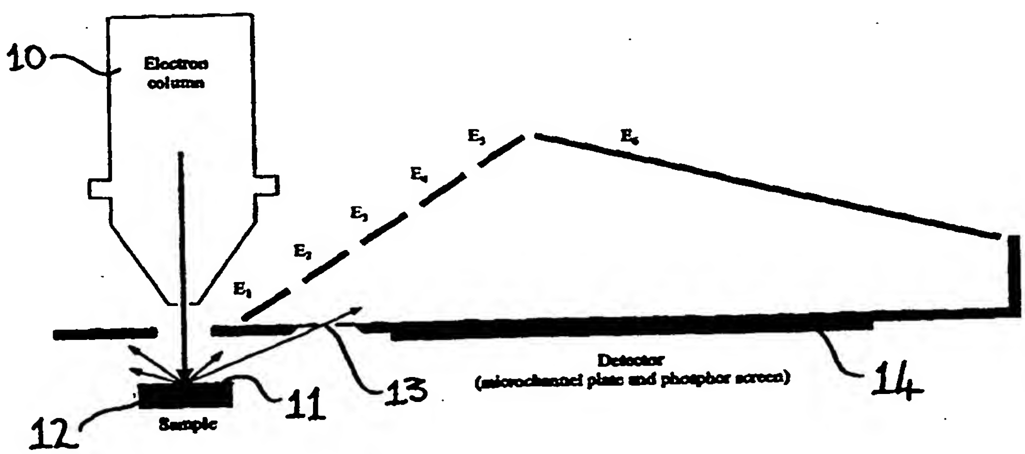
(54) Title: CHARGED PARTICLE ENERGY ANALYSERS



The prototype Hyperbolic Field Analyser

(57) Abstract

An electron energy analyser has an electron column (10) to excite a sample (11) on a sample holder (12). Excitation of the sample (11) causes electrons to be emitted, and some of the electrons enter the analyser through an aperture (13), where they are subjected to a substantially hyperbolic field defined with reference to an x–axis and a y–axis, each of which axes is at a substantially constant potential, and which is approximated with a small number of electrodes E_1 to E_6. The electrons are deflected by the substantially hyperbolic field to impinge upon a detector (14) which is arranged substantially along the x–axis and comprises, for example, a microchannel plate and phosphor screen, in the vicinity of which the electrons are focussed. The electrodes E_1 to E_5 are arranged in a plane which is inclined to the general axis of the analyser (i.e. the x–axis parallel to the detector (14)), and the electrode E_6 is similarly inclined, but in an opposite direction. The prime feature of the electron energy analyser is the ability to detect electrons with a large range of energies, in parallel.

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CHARGED PARTICLE ENERGY ANALYSERS

This invention relates to charged particle energy analysers.

Although charged particle spectrometers are commercially available with multichannel capabilities, the range of energies they can detect is typically only about 1% of a useful Auger spectrum (eg 50eV to 2050eV).

Preferred embodiments of the present invention aim to provide electron energy analysers or spectrometers whose prime feature is the ability to detect electrons with a large range of energies, in parallel. The main purpose envisaged is for the energy analysis of electrons scattered from a sample. The electrons may be generated by photons, electrons or other ionising radiation. The scattered electrons include secondary, back-scattered, Auger, loss and photoelectrons, with energies between about 10eV and 3000eV. With a collection efficiency (solid angle acceptance) comparable with existing spectrometers, preferred embodiments of the present invention may collect a full useful Auger spectrum in one process, and therefore operate approximately 100 times faster than existing spectrometers.

According to one aspect of the present invention, there is provided a charged particle energy analyser comprising:

a. field means for creating a substantially hyperbolic field defined with reference to an x-axis and a y-axis, each of which axes is at a substantially constant potential;

b. entry means for admitting charged particles into said field; and

c. detecting means arranged substantially along said x-axis, for detecting electrons deflected by said field.

Preferably, said field is at least partly electrostatic.

Said field may be at least partly magnetic.

Preferably, said entry means is arranged to admit charged particles into said field, at a region along said x-axis.

Preferably, said charged particles are electrons.

Preferably, said field is defined by the equations:

$V = V_1 a^{-n} r^n \sin(n\theta) \qquad (0 \leq \theta \leq \pi/n)$

$V = 0 \qquad (\pi/n < \theta < 2\pi)$

where V_1 is the potential of the line of equipotential whose closest point to the origin of the x,y axes is a distance a from it, $n = 2 \pm k$, and k is in the range 0 to 0.4.

Preferably, $k = 0.1$, 0.2, 0.3 or 0.4.

A charged particle energy analyser as above may include means for causing emission of said charged particles.

For a better understanding of the invention, and to show how embodiments of the same may be carried into effect, reference will now be made, by way of example, to the accompanying diagrammatic drawings, in which:

Figure 1 illustrates a hyperbolic electrostatic field;

Figure 2 illustrates focussing of electrons leaving an origin, such that first order focussing occurs at $\alpha = 24.78°$;

Figure 3 illustrates focussing of a parallel beam of electrons, such that first order focussing occurs at $\alpha = 21.51°$;

Figure 4 illustrates focussing of electrons originating from a point outside a field, such that first order focussing occurs at $21.51° \leq \alpha \leq 24.78°$;

Figure 5 illustrates one example of a substantially hyperbolic field within an analyser, by way of an elevation which shows an x-y view;

Figure 6 is a plan view of a detector and entrance aperture;

Figure 7 shows essential elements of one example of a substantially hyperbolic field analyser, and also shows some examples of electron trajectories;

Figure 8 shows energy dispersion (energy versus position) in one example of a hyperbolic field analyser;

Figure 9 shows energy resolution (energy versus energy resolution) in one example of a hyperbolic field analyser;

Figure 10 illustrates a prototype analyser with electron column and sample shown, in which a hyperbolic field is approximated with a small number of electrodes; and

Figure 11 shows a silver Auger spectrum obtained using the prototype analyser of Figure 10.

Figure 1 illustrates a two-dimensional hyperbolic electrostatic field defined with reference to an x-axis and a y-axis, each of which axes is at a substantially constant potential - typically zero potential. Such a field is used in preferred embodiments of the invention, examples of which are given below, to disperse electrons according to their energies. The potential distribution, which determines the field, is given by the following equations (in cylindrical polar form):

$$V = V_1 a^{-n} r^n \sin(n\theta) \qquad (0 \leq \theta \leq \pi/n)$$

$$V = 0 \qquad (\pi/n < \theta < 2\pi)$$

For a hyperbolic field, $n = 2$ and V_1 is the potential of the line of equipotential whose closest point to the origin of the axes is a distance a from it.

Equations for calculating the trajectories of electrons in such fields are well known and in fact a full quadrupole electrostatic field has long been used in a variety of applications involving the transport and dispersion of charged particles. Examples include 'strong' electrostatic lenses, beam deflectors and single channel energy analysers. Nevertheless, certain properties of the field of Figure 1, which represents only a quarter of a full quadrupole electrostatic field as traditionally used in the past in other applications, are central to the preferred embodiments of the present invention described below, and have not previously been recognised or exploited. These relate to the focussing of

beams of electrons having angular divergence or width in a way which is independent, or nearly so, of the energy of the electrons.

An important feature of preferred embodiments of the present invention, as described below, is the angle at which electrons are emitted into the hyperbolic field. Figures 2 to 4 illustrate the principle behind this.

As shown in Figure 2, electrons starting at the origin of the axes in the retarding field with initial trajectories at or about an angle $\alpha=24.78°$ with respect to the x-axis will be focussed onto the x-axis at a distance L from the origin. The length L is proportional to the square root of the energy of the electrons.

As shown in Figure 3, a parallel beam of electrons entering the retarding field at or about the origin of the axes with initial trajectories having an angle $\alpha=21.51°$ with respect to the x-axis will be focussed onto the x-axis at a distance L from the origin. The length L is again proportional to the square root of the energy of the electrons.

As shown in Figure 4, electrons originating from a point outside the field, at a perpendicular distance d from the x-axis, and entering the field near to the origin of the axes with an angle between $\alpha=21.51°$ and $\alpha=24.78°$ will be focussed to a point near the x-axis. The locus of focal points of different energy electrons depends on α, $\Delta\alpha$, x_0, d and the extremes of energies, E_{max} and E_{min}, of the electrons.

In all three cases of Figures 2 to 4, the focussing is only weakly dependent on a component of the motion in the z direction. The third

arrangement described above with reference to Figure 4 provides the basis for a practical analyser, since it allows for a point source of electrons at a finite distance from the entrance to the analyser. The first two cases of Figures 2 and 3 are in fact the extremes ($d=0$ and $d=\infty$) of the third arrangement of Figure 4.

One example of an electron energy analyser using such a hyperbolic electrostatic field is shown in Figure 5. The hyperbolic electrostatic field is created by applying appropriate voltages to electrodes E_0 to E_{10} arranged orthogonally in the x-y plane. In the z direction, the electrodes continue for some distance until the field in the centre is undistorted. It may be noted that the x and y potential gradients (E_0 to E_{10}) are linear. This is only one of many possible ways of creating the field. An entrance aperture is placed on the x-axis (in the x-z plane) centred at x_0. Because this is on an equipotential surface, and in the region of weakest electric field, the entrance aperture does not distort the field. This means that the energy resolution arising from the geometry of the hyperbolic field can be realised. The size and shape of the entrance aperture determines the solid angle acceptance of the analyser. The distance of x_0 from the origin is very much smaller than the average dispersion length - i.e. the distance between the entrance aperture and the middle of the detector area.

As shown in Figure 6, an electron detector is also placed along the x-axis in the x-z plane. The detector is able to resolve simultaneously the arrival of electrons landing in different locations on its front face. This may consist of a microchannel plate (to amplify the signal) followed by a phosphor screen. The light pattern on the screen may be measured using a photodiode array or CCD, either coupled directly to the screen, coupled via a fibre optic

bundle or using a conventional optical lens. Figure 6 is a schematic diagram of a plan view of the detector and entrance aperture showing the energy dependence of the location at which electrons are detected.

Some of the parameters for a typical arrangement suitable for the detection of Auger excited electrons are given in Table 1 below and some examples of electron trajectories are shown in Figure 7.

α	24.55°
$\Delta\alpha$	1°
ß	10°
d	8mm
x_0	1.2mm
E_{min}	50eV
E_{max}	2050eV
V_{max}	2400V

Table 1

For this arrangement the value of α is chosen to make the locus of focal points as near as possible to the detector face so as to maximise the energy resolution of the analyser. The solid angle acceptance in this case is ~0.05% of the full 2π steradians emitted from the surface of a sample. Both $\Delta\alpha$ and ß can be increased in order to collect more signal but, as with any analyser, this will affect the energy resolution achievable.

Figure 8 illustrates energy dispersion (energy versus position) in a hyperbolic field analyser having an arrangement as shown in Figure 4 and parameters according to Table 1.

Figure 9 shows the theoretical energy resolution (energy versus energy resolution) in a hyperbolic field analyser having an arrangement as shown in Figure 4 and parameters according to Table 1. This resolution is suitable for the detection and quantification of the chemical composition of the surface of a sample.

Figure 10 illustrates a prototype analyser with an electron column 10 to excite a sample 11 on a suitable sample holder 12. Excitation of the sample 11 causes electrons to be emitted, and some of the electrons enter the analyser through an aperture 13, where they are subjected to a substantially hyperbolic field which is approximated with a small number of electrodes E_1 to E_6. In a manner as described above, the electrons are deflected by the substantially hyperbolic field to impinge upon a detector 14 comprising, for example, a microchannel plate and phosphor screen, in the vicinity of which they are focussed.

As may be seen in Figure 10, the electrodes E_1 to E_5 are arranged in a plane which is inclined to the general axis of the analyser (i.e. the axis parallel to the detector 14), and the electrode E_6 is similarly inclined, but in an opposite direction.

Figure 11 shows a silver Auger spectrum obtained using the prototype analyser of Figure 10. In this example, the acquisition time was 2 seconds

and the primary electron beam 10nA, 5000eV. In Figure 11, only part of the spectrum is shown, although a full Auger spectrum from 50eV to 2050eV was collected in parallel, in the 2 second period. Substantially faster collection times are possible, using the same principle.

Variations to the above described embodiments of the invention are possible.

By slightly distorting the field or having n (in the equations above) slightly different to 2, the field will not be truly hyperbolic, yet the analyser may be made to work quite satisfactorily. Thus the value n may be replaced by $n \pm k$, where for example $k = 0, 0.1, 0.2, 0.3$ or 0.4.

Although the illustrated analysers are two-dimensional, to give a linear detection area, they may be rotated by up to 2π about their axis or any line which goes through the point source, to give a rotationally symmetrical version in which a spectrum may be collected on a disk, cylinder or other shaped collector or detector.

The electrostatic field may be replaced or supplemented by a magnetic field.

Alternative embodiments of the invention may receive, deflect and detect other charged particles (e.g. ions, positrons), or electrons with much higher or lower energy than in Auger spectroscopy.

It will be appreciated that, in the above examples, the x, y and z axes can have any absolute orientation in space, and are not necessarily as shown in the Figures.

In this specification, the term "detector" includes both a single detector and a set or array of detectors.

In this specification, the verb "comprise" has its normal dictionary meaning, to denote non-exclusive inclusion. That is, use of the word "comprise" (or any of its derivatives) to include one feature or more, does not exclude the possibility of also including further features.

The reader's attention is directed to all papers and documents which are filed concurrently with or previous to this specification in connection with this application and which are open to public inspection with this specification, and the contents of all such papers and documents are incorporated herein by reference.

All of the features disclosed in this specification (including any accompanying claims, abstract and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features and/or steps are mutually exclusive.

Each feature disclosed in this specification (including any accompanying claims, abstract and drawings), may be replaced by alternative features serving the same, equivalent or similar purpose, unless expressly stated otherwise. Thus, unless expressly stated otherwise, each feature

disclosed is one example only of a generic series of equivalent or similar features.

The invention is not restricted to the details of the foregoing embodiment(s). The invention extends to any novel one, or any novel combination, of the features disclosed in this specification (including any accompanying claims, abstract and drawings), or to any novel one, or any novel combination, of the steps of any method or process so disclosed.

CLAIMS

1. A charged particle energy analyser comprising:

   a. field means for creating a substantially hyperbolic field defined with reference to an x-axis and a y-axis, each of which axes is at a substantially constant potential;

   b. entry means for admitting charged particles into said field; and

   c. detecting means arranged substantially along said x-axis, for detecting electrons deflected by said field.

2. A charged particle energy analyser according to claim 1, wherein said field is at least partly electrostatic.

3. A charged particle energy analyser according to claim 1 or 2, wherein said field is at least partly magnetic.

4. A charged particle energy analyser according to any of the preceding claims, wherein said entry means is arranged to admit charged particles into said field, at a region along said x-axis.

5. A charged particle energy analyser according to any of the preceding claims, wherein said charged particles are electrons.

6. A charged particle energy analyser according to any of the preceding claims, wherein said field is defined by the equations:

$$V = V_1 a^{-n} r^n \sin(n\theta) \qquad (0 \leq \theta \leq \pi/n)$$

$$V = 0 \qquad (\pi/n < \theta < 2\pi)$$

where V_1 is the potential of the line of equipotential whose closest point to the origin of the x,y axes is a distance a from it, $n = 2 \pm k$, and k is in the range 0 to 0.4.

7. A charged particle energy analyser according to claim 6, where $k = 0.1, 0.2, 0.3$ or 0.4.

8. A charged particle energy analyser according to any of the preceding claims, including means for causing emission of said charged particles.

9. A charged particle energy analyser substantially as hereinbefore described with reference to any of Figures 1 and 4 to 11 of the accompanying drawings.

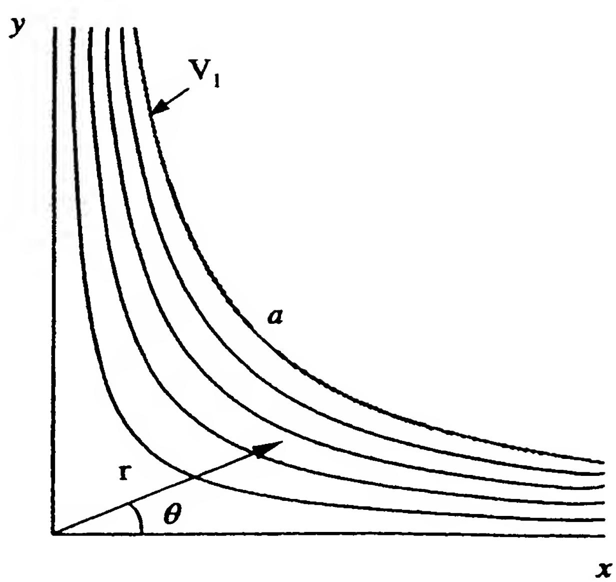

Figure 1: The hyperbolic electrostatic field

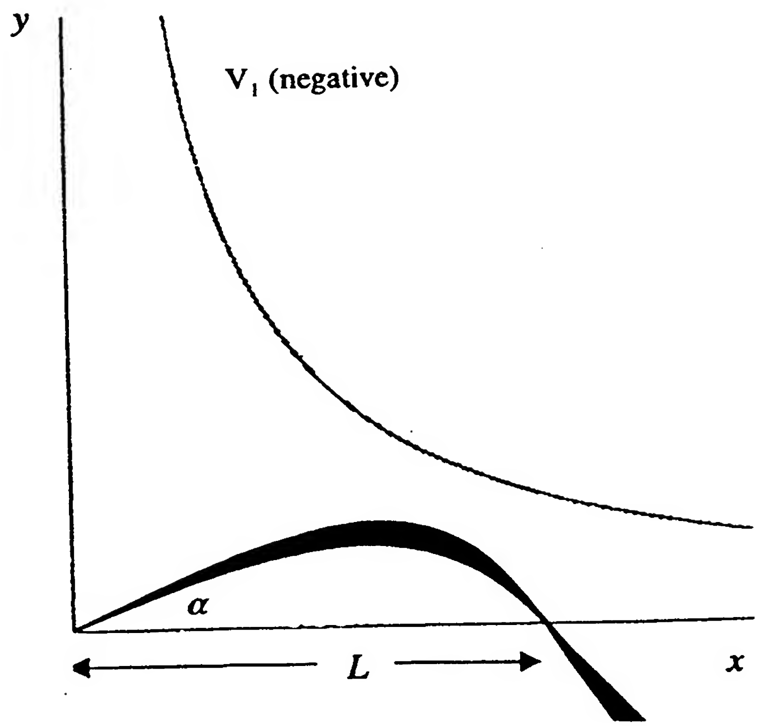

Figure 2:

Focussing electrons leaving the origin. First order focussing occurs at $\alpha = 24.78°$

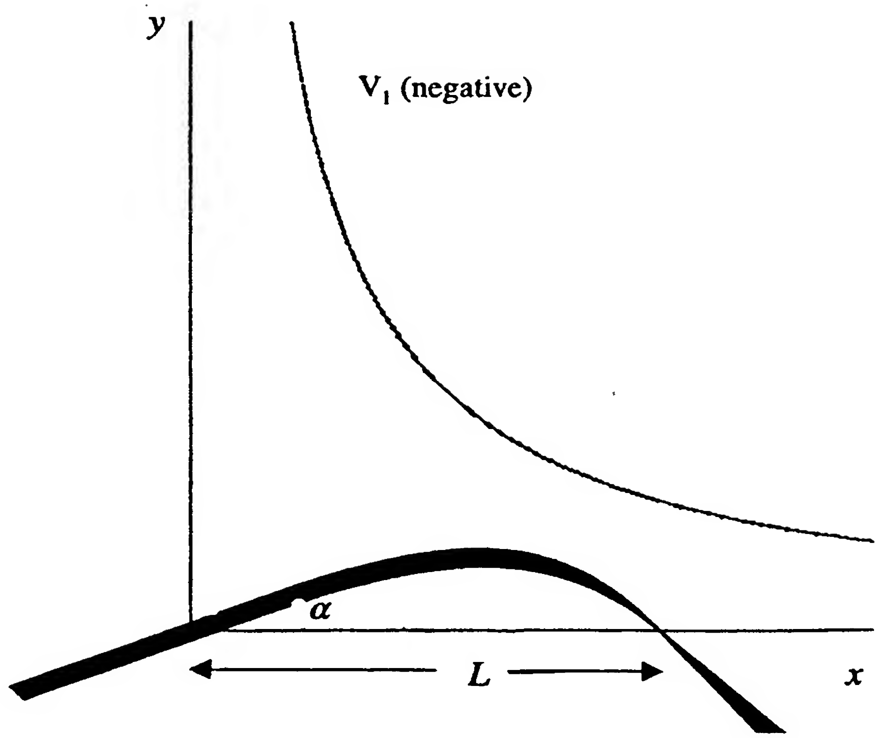

Figure 3:

Focussing of a parallel beam of electrons. First order focussing occurs at α=21.51°

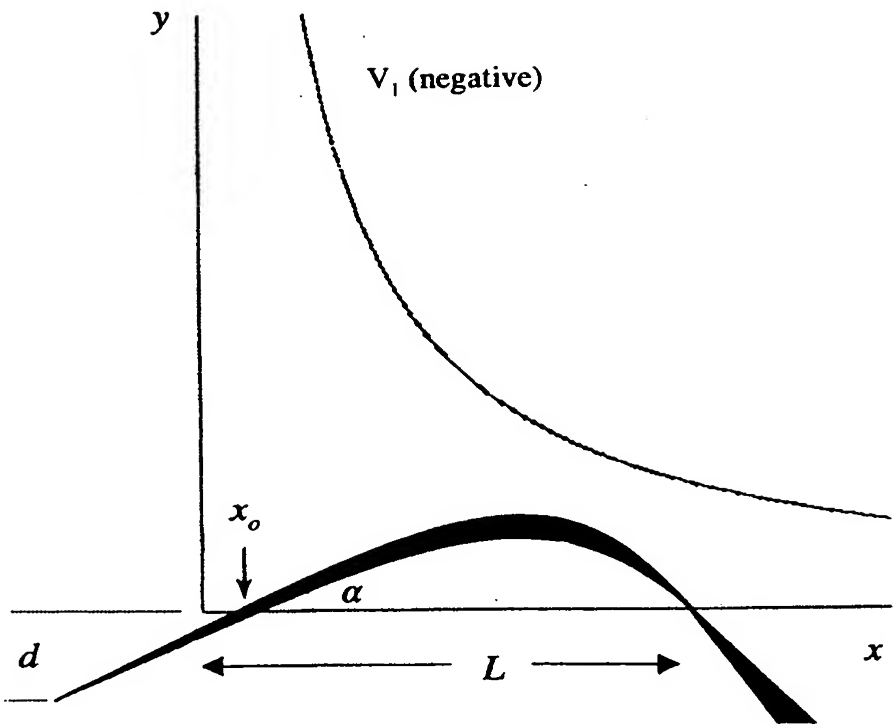

Figure 4:

Focussing of electrons originating from a point outside the field. $21.51° \leq \alpha \leq 24.78°$

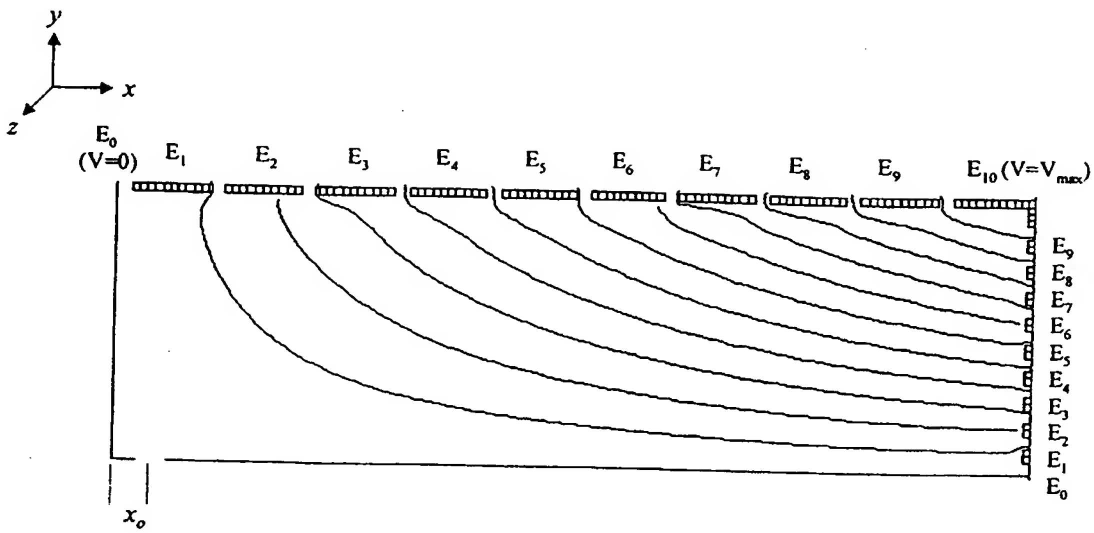

Figure 5: The field within the analyser. This elevation shows the *x-y* view. In the *z* direction the electrodes continue for some distance until the field in the centre is undistorted.

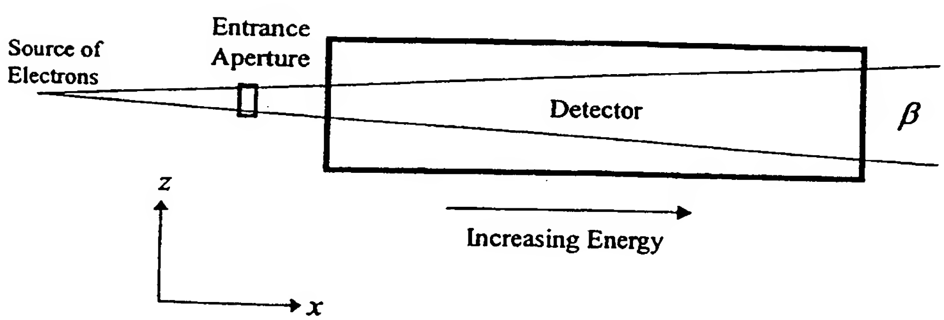

Figure 6: Plan view of the detector and entrance aperture.

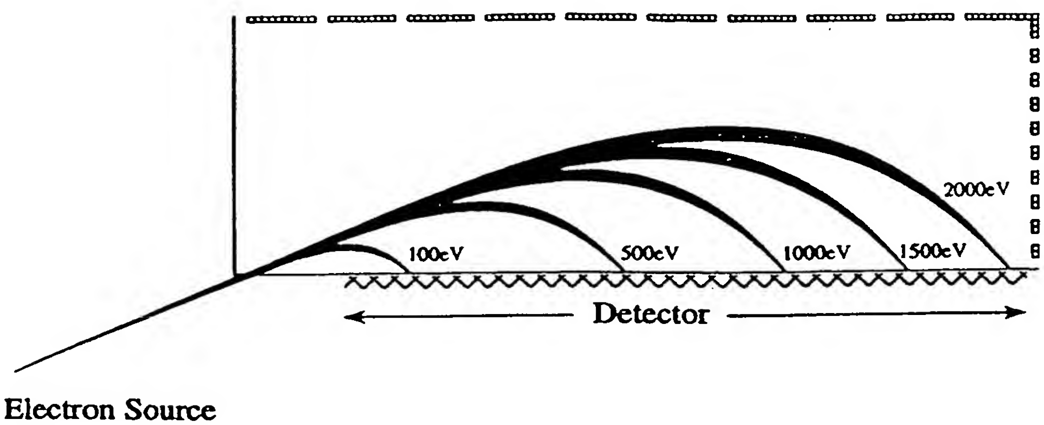

Figure 7:

The essential elements of the analyser, also showing some examples of electron trajectories

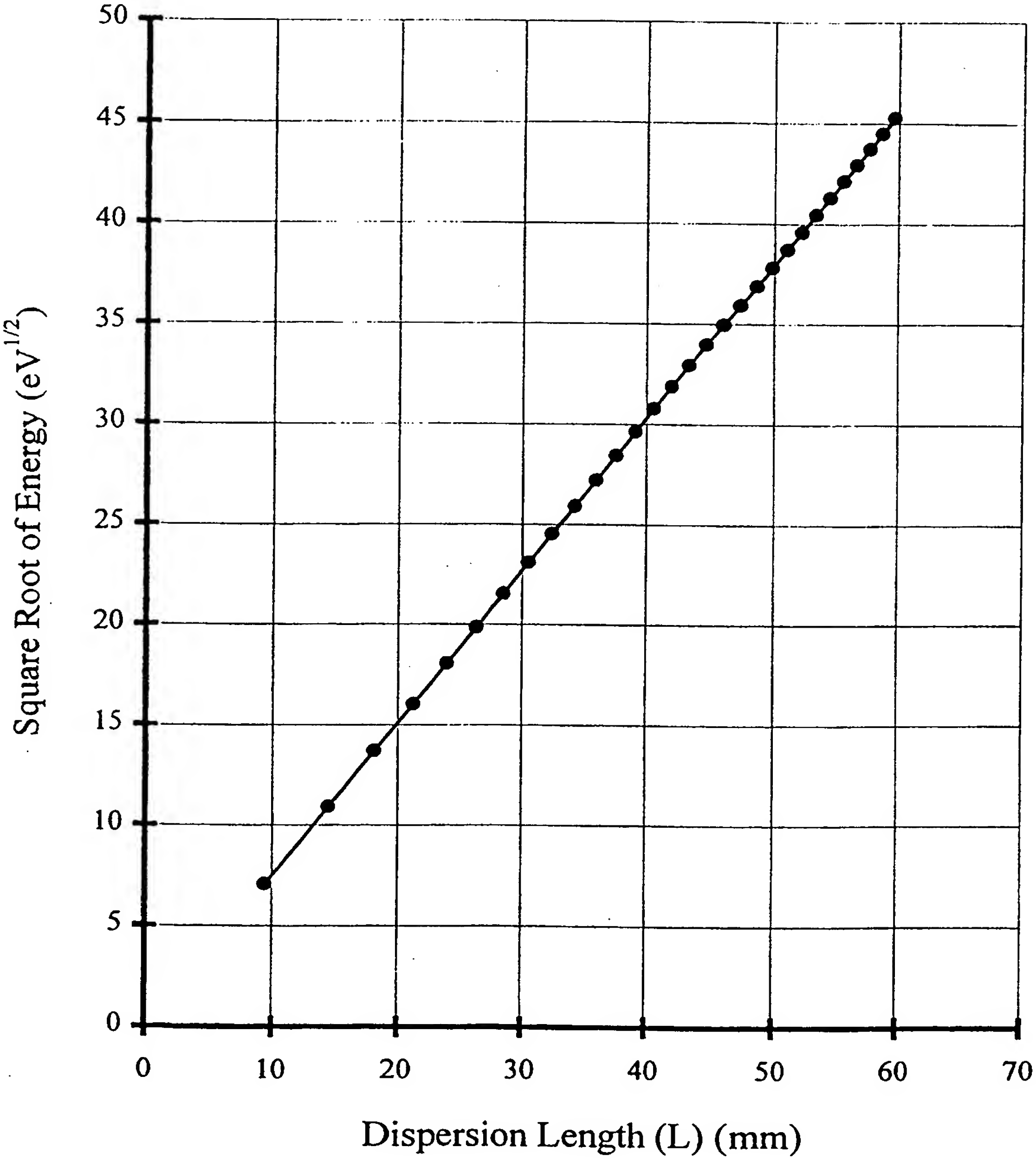

Figure 8: Dispersion of the HFA (see Figure 4) for the parameters in Table 1.

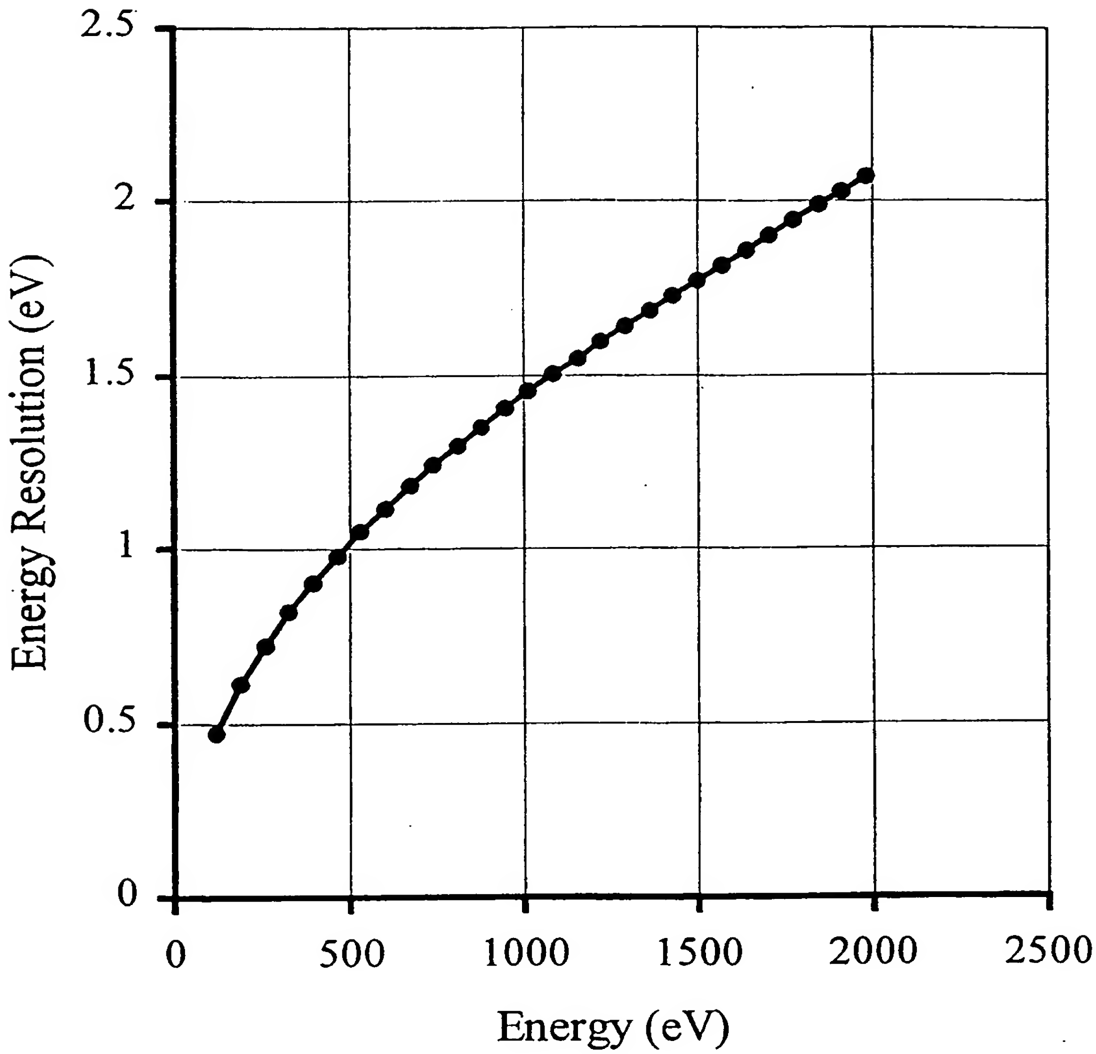

Figure 9: Theoretical energy resolution achievable with the HFA for the parameters in Table 1.

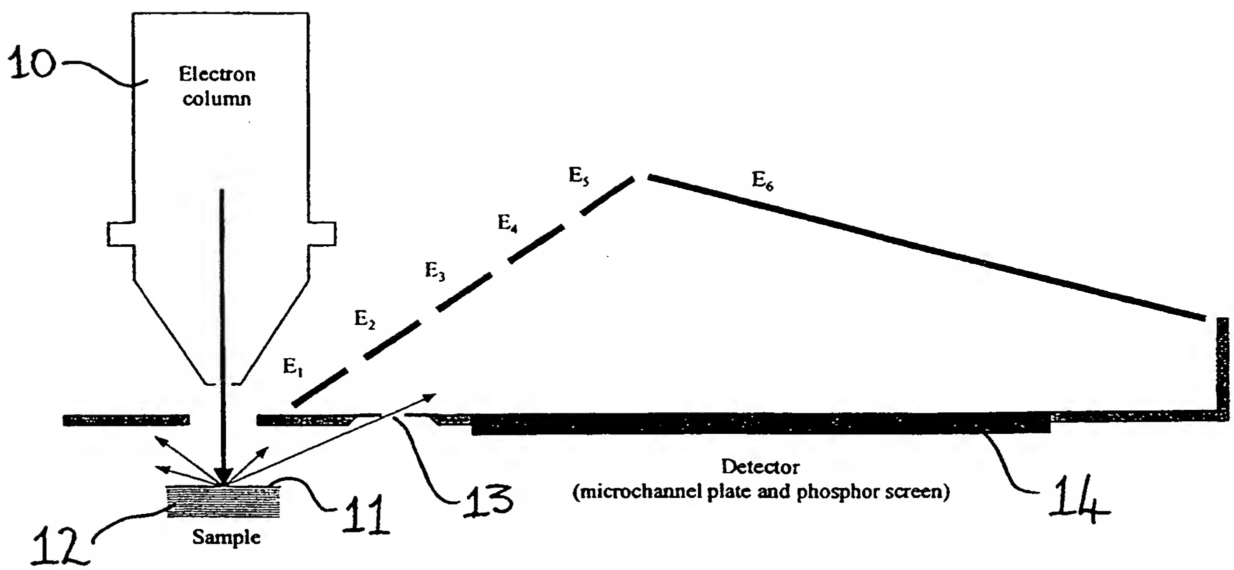

Figure 10: The prototype Hyperbolic Field Analyser.

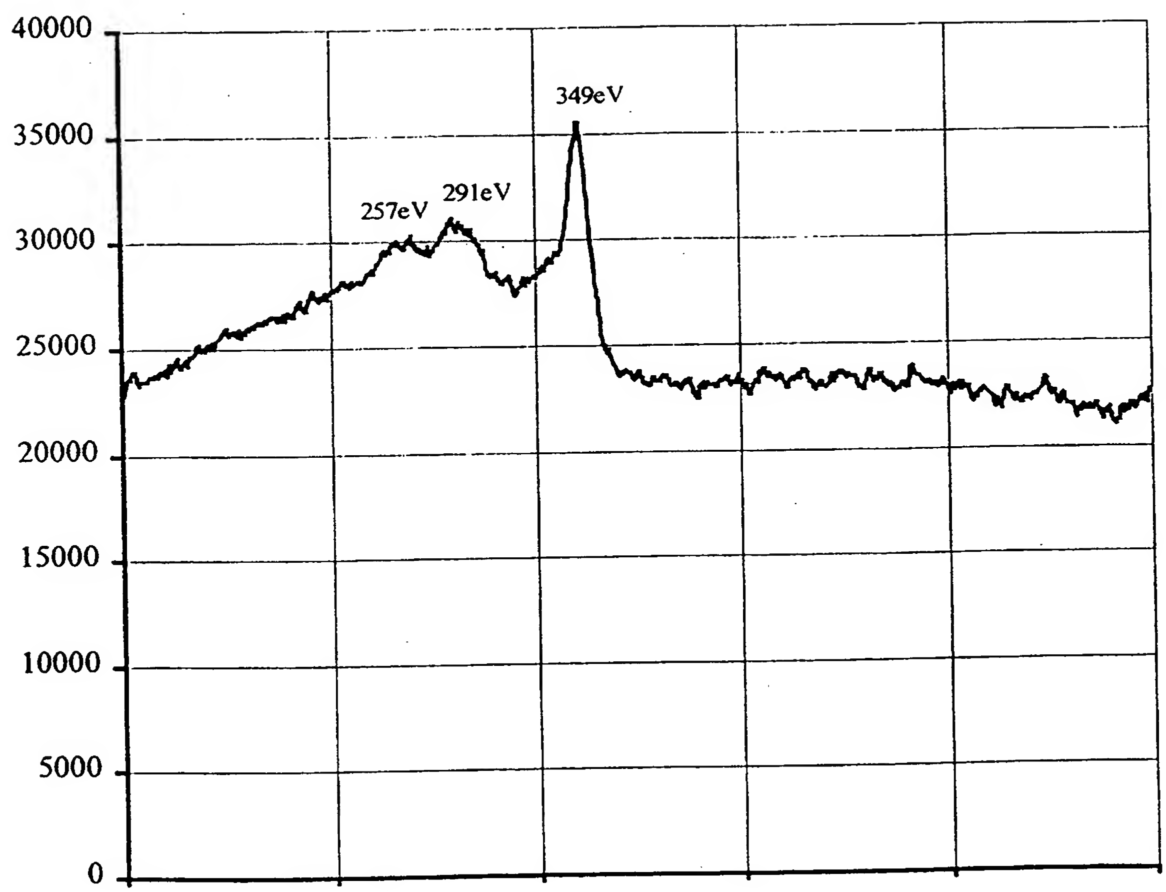

Figure 11: Silver Auger spectrum acquired using the prototype Hyperbolic Field Analyser (Figure 10). The acquisition time was 2 seconds and the primary electron beam 10nA, 5000eV. Note that only part of the spectrum is shown although all is collected in parallel.

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 99/00009

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01J49/48

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	HAMILTON D C ET AL: "NEW HIGH-RESOLUTION ELECTROSTATIC ION MASS ANALYZER USING TIME OF FLIGHT" REVIEW OF SCIENTIFIC INSTRUMENTS, vol. 61, no. 10 PART 02, 1 October 1990 (1990-10-01), pages 3104-3106, XP000171706 ISSN: 0034-6748 page 3104, left-hand column, last paragraph --- -/--	1,2

[X] Further documents are listed in the continuation of box C.

[ ] Patent family members are listed in annex.

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3 August 1999	11/08/1999

Name and mailing address of the ISA	Authorized officer
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	MOBIUS E ET AL: "HIGH MASS RESOLUTION ISOCHRONOUS TIME-OF-FLIGHT SPECTROGRAPH FOR THREE-DIMENSIONAL SPACE PLASMA MEASUREMENTS" REVIEW OF SCIENTIFIC INSTRUMENTS, vol. 61, no. 11, 1 November 1990 (1990-11-01), pages 3609-3612, XP000174341 ISSN: 0034-6748 abstract page 3610; figure 1 ---	1,2
X	LEAL-QUIROS E ET AL: "A HYPERBOLIC ENERGY ANALYZER" REVIEW OF SCIENTIFIC INSTRUMENTS, vol. 61, no. 6, 1 June 1990 (1990-06-01), pages 1708-1712, XP000166153 ISSN: 0034-6748 page 1708 -----	1

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